FLASH OF PHOTONS FROM THE EARLY STAGE OF HEAVY-ION COLLISIONS

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The dynamics of partonic cascades may be an important aspect for particle production in relativistic collisions of nuclei at CERN SPS and BNL RHIC energies. Within the *Parton-Cascade Model*, we estimate the production of single photons from such cascades due to scattering of quarks and gluons $q\ g \ \rightarrow \ q\ \gamma$, quark-antiquark annihilation $q\ \bar{q} \ \rightarrow \ g\ \gamma$ or $\gamma\gamma$, and from electromagnetic brems-strahlung of quarks $q \ \rightarrow \ q\ \gamma$. We find that the latter QED branching process plays the dominant role for photon production, similarly as the QCD branchings $q \rightarrow qg$ and $g \rightarrow gg$ play a crucial role for parton multiplication. We conclude therefore that photons accompanying the parton cascade evolution during the early stage of heavy-ion collisions shed light on the formation of a partonic plasma.

Photons have remained one of the most effective probes of every kind of terrestrial or celestial matter over the ages. Thus, it is only befitting that the speculation of the formation of deconfined strongly interacting matter - some form of the notorious quark-gluon plasma - in relativistic heavy-ion collisions, was soon followed by a suggestion [1] that it should be accompanied by characteristic production of photons. The effectiveness of photons in probing the history of such a hot and dense matter stems from the fact that, after production, they leave the system without any further interaction and thus carry unscathed information about the circumstances of their birth. This is a very important consideration indeed, as the formation of a partonic plasma is likely to proceed from a hard-scattering of initial partons, through a pre-equilibrium stage, to perhaps a thermally and chemically equilibrated state of hot and dense partonic matter. In this letter we concentrate on photons coming from the early partonic stage in such collisions. We will not consider other sources of photons, e.g., those that accompany the late hadronic stage, after the partons have hadronized.

During the partonic stage, photons emerge from two different mechanisms: firstly, from collisions between partons, i.e., Compton scattering $qg \rightarrow q\gamma$ of quarks and gluons and annihilation $q\bar{q} \rightarrow g\gamma$, $q\bar{q} \rightarrow \gamma\gamma$ of quarks and antiquarks; secondly, from radiation of excited partons, i.e. electromagnetic brems-strahlung $q \rightarrow q\gamma$ of time-like cascades initiated by quarks. Whereas the former mechanism has been studied in various contexts [2], the latter source of photons is less explored [3], although, as we shall show, it is potentially much richer both in magnitude and complexity.

A dynamical description of relativistic heavy-ion collisions has been developed in the *Parton Cascade Model* (PCM) [4]. The PCM is based on the parton picture of hadronic interactions and describes the nuclear dynamics in terms of the interaction of quarks and gluons within perturbative quantum chromodynamics, embedded in the framework of relativistic quantum kinetics [5]. The time evolution of the system is followed by Monte Carlo simulation of a set of equations describing space-time development and renormalization-group evolution of the particles. The procedure, implemented in a computer code VNI [6], traces the dynamic evolution of partons scattering, radiating, fusing, and eventually clustering to pre-hadronic states that then produce the final-state hadron yield. VNI, the Monte Carlo implementation of the PCM, has been adjusted on the basis of experimental data from e^+e^- annihilation and pp ($p\bar{p}$) collisions. In the past, the PCM has been used to provide insight [4] into conditions likely to be achieved at RHIC and LHC energies $\sqrt{s} = 200$ A GeV, respectively $\sqrt{s} = 5$ A TeV. Only very recently, it has been found [7] to provide as well a reasonable description to a large body of particle spectra from $Pb + Pb$ and $S + S$ collisions at CERN-SPS energy $\sqrt{s} \simeq 18$ A GeV, in contrast to the belief that the PCM could not be applied at energies $\sqrt{s} \lesssim 100$ A GeV. A valuable advantage of the PCM is that it is free of assumptions about thermal or chemical equilibrium conditions, since the space-time evolution of the matter is traced causally from the moment of collision on, so that at any point the state of the matter is unambiguously determined by the preceding space-time history.

Prompt photons from both parton collisions and brems-strahlung are ideally suited to test the evolution of the partonic matter as described by the PCM. They would accompany the early hard scatterings, the approach to thermalization and chemical equilibration if these are achieved at all.

We first discuss the aspect of *collisional photon production* from parton collisions. This is straightforward, and is included in the PCM in terms of the elementary $2 \rightarrow 2$ processes which yield photons, that is, the annihilation and Compton processes, $q\bar{q} \rightarrow g\gamma$, $q\bar{q} \rightarrow \gamma\gamma$, $qg \rightarrow q\gamma$, the Born cross-sections of which are well-known [8]. In the PCM approach we treat these processes within perturbative QCD if the momentum $q_\perp$ transferred in the parton collision is larger than some cut-off $q_\perp^0$ [4]. (This cut-off is introduced in the c.m. frame of the colliding

partons, and thus we may have contributions even for smaller transverse momentum in the nucleus-nucleus c.m. frame.)

Next we turn to the aspect of *radiative photon emission* from parton showers initiated by collisions, which is a more complex issue. There are some important and interesting differences between a branching leading to production of photons as compared to gluons, which have been pointed out in detail by Sjöstrand [3].

(i) Consider an energetic quark produced by a hard scattering, which can radiate gluons and photons competitively. The branchings $q \to qg$ and $q \to q\gamma$ appear in the PCM on an equal footing and as competing processes with similar structures. The probability, for a quark to branch at some given virtuality scale Q^2, with the daughter quark retaining a fraction z of the energy of the mother quark, is given by:

$$d\mathcal{P} = \left(\frac{\alpha_s}{2\pi}C_F + \frac{\alpha_{\rm em}}{2\pi}e_q^2\right)\frac{dQ^2}{Q^2}\frac{1+z^2}{1-z}dz \qquad (1)$$

where the first term corresponds to gluon emission and the second to photon emission. Thus, the relative probability for the two processes is,

$$\frac{\mathcal{P}_{q\to q\gamma}}{\mathcal{P}_{q\to qg}} \propto \frac{\alpha_{\rm em}\langle e_q^2\rangle}{\alpha_s C_F} \simeq \frac{1}{200}\,, \qquad (2)$$

using $\alpha_{\rm em} = 1/137$, $\alpha_s = 0.25$, $\langle e_q^2\rangle = 0.22$ and $C_F = 4/3$. Thus, we notice that the emission of photons is strongly affected by the perturbative QCD effects. This does not mean, though, that we can simulate emission of photons in a QCD shower by simply replacing the strong coupling constant α_s with the electromagnetic $\alpha_{\rm em}$ and the QCD color Casimir factor $C_F = 4/3$ by e_q^2. One has to keep in mind that the gluon, thus emitted, may branch further either as, $g \to gg$ or as $g \to q\bar{q}$, implying that the emitted gluon has an effective non-zero mass. As the corresponding probability for the photon to branch into a quark or a lepton pair is very small, this process is neglected and the photon is taken to have a zero mass. (However, if we wish to study the dilepton production from the collision, this may become an important contribution [9]).

(ii) The radiation of gluons from the quarks is subject to soft-gluon interference which is accounted for by imposing an angular ordering of the emitted gluons. This is not so for the emitted photons. To recognize this aspect, consider a quark which has already radiated a number of hard gluons. The probability to radiate and additional softer gluon will get contributions from each of the existing partons which may further branch as $q \to qg$ or $g \to gg$. It is well-known [10] that if such a soft gluon is radiated at a large angle with respect to all the other partons and one would add the individual contributions incoherently, then the emission rate would be overestimated, as the interference is destructive. This happens because a soft gluon of a long wavelength is not able to resolve the individual color charges and observes only the net charge. The probabilistic picture of PCM is then recovered by demanding that emissions are ordered in terms of decreasing opening angle between the two daughter partons at each branching, i.e., restricting the phase-space allowed for the successive branchings. The photons, on the other hand, do not carry any charge and only the quarks radiate. Thus photons are not subject to angular ordering. Pictorially, the branching structure in QCD is 'pine-tree' like, whilst in QED it is 'oak-tree' like.

(iii) The parton emission probabilities in the QCD showers contain soft and collinear singularities, which are regulated by introducing a cut-off scale μ_0. This regularization procedure implies effective masses for quarks and gluons,

$$m_{\rm eff}^{(q)} = \sqrt{\frac{\mu_0^2}{4} + m_q^2}\,, \qquad m_{\rm eff}^{(g)} = \frac{\mu_0}{2}\,, \qquad (3)$$

where m_q is the current quark mass. Thus the gluons cannot branch unless their mass is more than $2m_{\rm eff}^{(g)} = \mu_0$, while quarks cannot branch unless their mass is more than $m_{\rm eff}^{(q)} + m_{\rm eff}^{(g)}$. An appropriate value for μ_0 is about 1 GeV [4]; a larger value is not favored by the data, and a smaller value will cause the perturbative expression to blow up. These arguments, however, do not apply for photon emission, since QED perturbation theory does not break-down and photons are not affected by confinement forces. Thus, in principle quarks can go on emitting photons till their masses reduce to current quark masses (or, in a dense matter environment, to the corresponding 'in-medium' Debye mass). It has also been suggested that if the confinement forces screen the bare quarks, the effective cut-off can be of the order of a GeV. These arguments suggest that we can choose the cut-off scale μ_0 in (3) separately for the emission of photons and that the study of photon emission can provide valuable insight about confinement at work by comparing the characteristics of gluon versus photon radiation from quarks.

We now turn to our results which we present in four examples: $S+S$ ($\sqrt{s} = 20$ A GeV) and $Pb+Pb$ collisions ($\sqrt{s} \simeq 18$ A GeV) at CERN-SPS, as well as $S+S$ and $Au+Au$ collisions at RHIC energy $\sqrt{s} = 200$ A GeV. For the following, it is useful to keep in mind, that the initial partonic composition of the colliding nuclei is very different for the two energies: at SPS, by far the main component are the quarks, with relative proportions $N_q : N_g \approx 1 : 0.4$, whereas at RHIC, the gluons play the dominant role, with $N_q : N_g \approx 1 : 1.9$.

In Fig. 1 we have plotted the production of single photons from such a partonic matter in the central rapidity region for $Pb+Pb$ system at SPS energy. The dot-dashed histogram shows the contribution of Compton and annihilation processes mentioned above. The dashed and the solid histograms show the total contributions (i.e., including the branchings $q \to q\gamma$) when the mass scale μ_0 in (3) for the photon production is taken respectively

as 0.01 and 1 GeV. We see that prompt photons from the quark branching completely dominate the yield for $p_\perp \leq 3$ GeV, whereas at larger transverse momenta the photons coming from the collision processes dominate. The reduction of μ_0 for the $q \to q\gamma$ branching is seen to enhance the production of photons have lower transverse momenta as one expects. We have also shown the production of single photons from pp collisions for $\sqrt{s} \approx 24$ GeV, obtained by WA70 [11], NA24 [12], and UA6 [13] collaborations scaled by the nuclear overlap for zero impact parameter for the collision of lead nuclei. The solid curve gives the perturbative QCD results [14] for the pp collisions scaled similarly. The dashed curve is a direct extrapolation of these results to lower $p_\perp$.

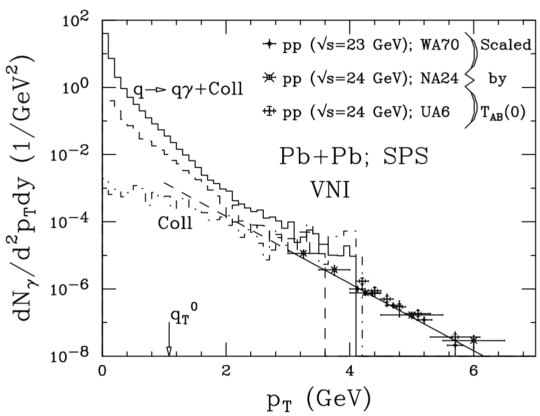

FIG. 1. The radiation of prompt photons from partonic matter in central collision of Pb (156 GeV/nucleon)+Pb nuclei at CERN SPS. The dot-dashed histogram gives the contribution of only the collision processes. The dashed and the solid histograms give the contribution of the collision plus branchings when the μ_0 for the $q \to q\gamma$ branching is taken as 1 and 0.01 GeV respectively. The pp data at $\sqrt{s} \approx 24$ GeV scaled by the nuclear overlap function for the central collision of lead nuclei and the corresponding QCD predictions (solid curve, arbitrarily extended to lower p_T) also shown for a comparison. q_T^0 denotes the transverse momentum cut-off above which the hard scatterings are included in the PCM.

In Fig. 2 we have plotted the transverse momenta of the single photons in several rapidity bins for $Pb + Pb$ and $S + S$ systems at SPS energy. We see that the transverse spectra scale reasonably well with the ratio of the nuclear overlap for central collisions for the two systems $T_{\rm PbPb}/T_{\rm SS} \approx 15.4$, which is indicative of the origin of these photons basically from a collision mechanism. The slight deviation from this scaling seen at lower $p_\perp$ results in a $\approx 20\%$ increase in the integrated yield at central rapidities. This is a good measure of the multiple scatterings in the PCM. In fact we have found that the number of hard scatterings in the $Pb + Pb$ system is ≈ 17 times more than that for the $S + S$ system, which also essentially determines the ratio of the number of the photons produced in the two cases. We also note that the inverse slope of the $p_\perp$ distribution decreases at larger rapidities, which is suggestive of the fact that the densest partonic system is formed at central rapidities.

Finally in Fig. 3 we have plotted our results for $S + S$ and $Au + Au$ systems at RHIC energy in the same fashion as Fig. 2. We see that the inverse slope of the $p_\perp$ distribution is now larger and drops only marginally at larger rapidities, indicating that the partonic system is now more dense and spread over a larger range of rapidity. Even though the $p_\perp$ distribution of the photons is seen to roughly scale with the ratio of the nuclear overlap functions for central collisions $T_{\rm AuAu}/T_{\rm SS} \approx 14.2$, the integrated yield of photons for the $Au + Au$ is seen to be only about 12 times that for the $S + S$ system at the RHIC energy. We have again checked that the number of hard scatterings for the $Au + Au$ system is also only about 12 times that for the $S + S$ system.

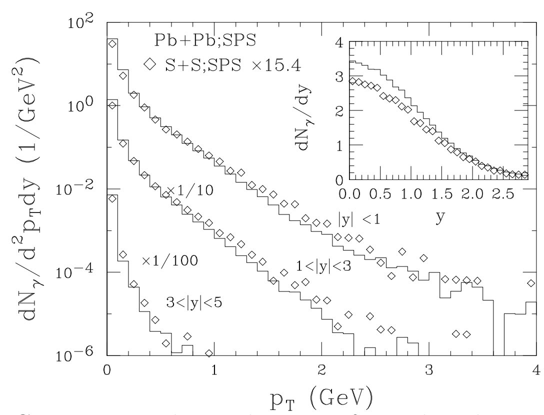

FIG. 2. The radiation of single photons from $S + S$(200 GeV/A) and $Pb + Pb$(158 GeV/A) collisions in different rapidity bins. The inset shows the rapidity distribution of the radiated photons. The results for the $S + S$ collisions have been scaled by the ratio $T_{\rm PbPb}/T_{\rm SS} \approx 15.4$ for central collisions. μ_0 for the quark branching $q \to q\gamma$ is taken as 0.01 GeV.

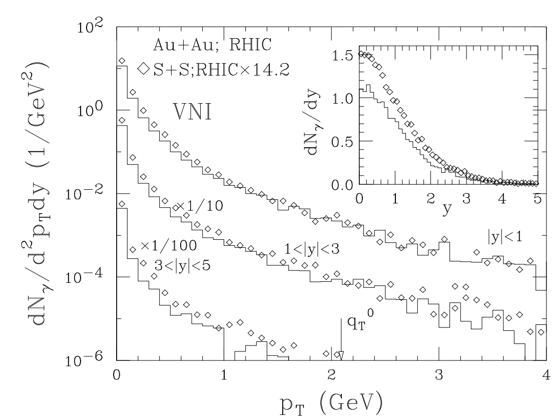

FIG. 3. The radiation of single photons from $S+S$ and $Au+Au$ collisions in different rapidity bins at RHIC energy $\sqrt{s}=200$ A GeV. The inset shows the rapidity distribution of the radiated photons. The results for the $S+S$ collisions have been scaled by the ratio $T_{\rm AuAu}/T_{\rm SS} \approx$ 14.2 for central collisions. μ_0 for the quark branching $q \rightarrow q\gamma$ is taken as 0.01 GeV.

This contrasting behavior at SPS and RHIC energies exhibited in the figures can be understood as follows. At the SPS, the partonic system can reach energy densities up to 5 GeV/fm^3 [7], and multiple scatterings become important, especially for heavier colliding nuclei. At RHIC, the energy density can easily become twice as large, and the Landau-Pomeranchuk suppression may play a counteracting role. In the PCM this effect is mimicked, rather crudely, by inhibiting a new scattering of partons till the passage of their formation time after a given scattering. In a future publication [15] we shall report on a possibility of seeing these competitive mechanisms at work by comparing results at different impact parameters for the same colliding nuclei, or for zero impact paramenter for different colliding nuclei.

Some other observations are worthwhile commenting on: Firstly, recall such branchings of the partons produced in hard collisions correspond to a next-to-leading-order correction in α_s. These are known to be considerably enhanced for collinear emissions. The parton shower mechanism incorporated in the PCM amounts to including these enhanced contributions to all orders, instead of including all the terms for a given order [16]. It may also be added that the first-order corrections to the Compton and annihilation processes in the plasma have been studied by a number of authors [17]; however in the plasma, $\langle q_\perp^2 \rangle \approx 4T^2$, thus their contribution is limited to very low transverse momentum. Clearly, $\langle q_\perp^2 \rangle$ is much larger in the early hard scatterings, and thus the radiations from the emerging partons are much more intense and also populate higher transverse momenta, as seen in the present work. The large yield of photons from the branching of energetic quarks preceding the formation of dense partonic matter opens an interesting possibility to look for a similar contribution to dilepton (virtual photon) production in such collisions.

We conclude that the formation of a hot and dense partonic system in relativistic heavy-ion collisions may be preceded by a strong flash of photons following the early hard scatterings. Their yield will, among several other interesting aspects, also shed light on the extent of multiple scattering encountered in these collisions [15]. However, we stress that we have only included the contribution of photons from the partonic interactions in this work. It is quite likely that the hadrons produced at the end will also interact and produce photons, as has been studied recently [18]. A comparison of those results with the present work shows that at the SPS energy the emission from the early hard partonic scatterings is of the same order as the photon production from later hadronic reactions, for $p_\perp \leq$ 2–3 GeV, and dominates considerably over the same at higher transverse momenta.

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